A validation study for the estimation of uniaxial compressive strength based on index tests

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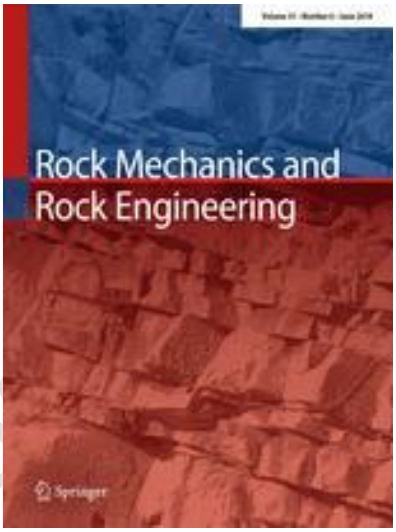

Keywords: uniaxial compressive strength; point load index; Schmidt hammer; regression analysis

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1 Introduction

Uniaxial compressive strength (UCS) is one of the crucial parameters controlling the strength of rock masses (Hu et al. 2012). A reliable and direct measurement of this parameter in the laboratory requires well-prepared samples and certified testing apparatus (Heidari et al. 2012). As an indirect method, index tests have been widely used to estimate the UCS of rock, especially in the field. The index tests can be performed using simple equipment such as portable point load testers and Schmidt hammers. Up to now, the relationship between UCS and the results of index tests has been widely discussed (Hoek 1977; Aggistalis et al. 1996; Fener et al. 2005; Karaman and Kesimal 2015). The validity of the index tests however remains poorly understood; results of the tests may vary due to lithological heterogeneity mainly arising from geological bedding and schistosity, grain size variation and micro-fractures. For example point load test results may vary significantly (by a factor up to 2) when samples drilled with different orientations relative to bedding planes are used (Broch 1983). Broch (1983) pointed out that the most reliable strength index can be obtained when samples are drilled normal to bedding planes. In addition, when a tested rock surface contains coarse grains with sizes comparable to the plunger tip diameter, the readings of Schmidt hammers can vary significantly, depending on their strength relative to the dominant grain size of the tested rock (Aydin 2009). Situations become worse when micro-fractures exist (unseen by the naked eye). It is therefore questionable about the validity of the index tests in the estimation of UCS, because the variation of the index test results can be attributed to (1) lithological heterogeneity of the tested rock samples (as described above) and (2) the validity of the index tests themselves.

To remove the effects of lithological heterogeneity and grain size that arise when using the index tests, we propose to “test the tests” using a range of “standard” bricks, which are available and can provide uniform, fine-grained and homogeneous media. A series of laboratory experiments were performed on these brick samples. The use of the uniform and homogeneous bricks allows the validity of the index tests to be tested, since the lithological heterogeneity has been removed as mentioned earlier. An evaluation study was conducted to assess the rational of using bricks for this study. Based on these experiments, relationships between UCS and the results of index tests are derived. The results are compared with those from literature.

2 A brief review of index tests

2.1 Point load test

Point load tests have been widely used in the estimation of UCS of rock both in the laboratory and in the field (Kahraman 2001). The study of point load tests can be divided into three stages. The first-stage study focused on theoretical formulations for estimating UCS from the point load index (I_S) (D’Andrea et al. 1964; Deere and Miller 1966). The second-stage investigation involved the correction of I_S due to its size-dependent nature, which was noted during the first-stage study. A standardized point load index ($I_{S(50)}$) was proposed, and measurement of this index is based on a rock core with a diameter of 50 mm (Broch and Franklin 1972; Bieniawski 1975; Brook 1980). It was also noted that the equations for correlating UCS and $I_{s(50)}$ are not consistent for rocks with different geological origins (Greminger 1982; ISRM 1985). Therefore, in the third-stage study, different equations were proposed for rocks with different geological formations (see Table 1). As shown in Table 1, the correlation factors between UCS and $I_{s(50)}$ vary significantly, ranging from 5 to 68.

2.2 Schmidt hammer test

Schmidt hammer tests are often used to estimate the strength of rock in the field (Sheorey et al. 1984; Cargill and Shakoor 1990). The Schmidt hammer imparts kinetic energy through a plunger when it is pressed against a rock surface. In each impact, a rebound value (*R*) reflecting the hardness of the surface can be read directly on the device. Two types of Schmidt hammers are commercially available (i.e., L-type and N-type) and they possess impact energy of 0.735 and 2.207 Nm, respectively (Aydin 2009). So far, many different equations have been proposed to correlate UCS and *R* for different rocks. Table 2 shows these equations.

3 Laboratory experiment

A series of uniaxial compression tests, point load tests and Schmidt hammer tests were conducted on the selected homogeneous bricks. The uniaxial compression experiments were carried out according to the standard of the American Society for Testing and Materials (ASTM 1995). Cylindrical brick samples with a diameter of 38 mm and a height-to-diameter ratio of 2.5 were prepared. Ends of the samples were ground flat and these samples were uniaxially compressed with a constant loading rate of 0.1 mm/min by a compression machine (model: Dennison 7227C) with a maximum loading capacity of 2000 KN. Axial load, strain and lateral strain were monitored during each test (see Fig 1). Figs 2a and 2b show the representative stress-strain curves of brick samples tested. The test was repeated more than 10 times for each sample and Table 3 shows the UCS of the tested brick samples. For comparison, uniaxial compression tests were also performed on Magnesian limestone and Woodkirk sandstone; both of the prepared rock samples are ostensibly homogeneous. A similar testing process to that of brick samples was followed and the stress-strain curves were logged. Figs 2c and 2d show the typical stress-strain curves of the tested rock samples.

Axial point load tests were then performed (International Society for Rock Mechanics-ISRM 2007). Brick samples with a diameter (*D*) of 38 mm and a length-to-diameter ratio of 0.5 were prepared in the tests. Peak loads (*P*) at the point of sample failure were logged. The test was repeated at least ten times for each brick sample and the standardized point load index ($I_{s(50)}$) of each test was calculated by using (see Table 3):

$$I_{\mathrm{s}(50)} = F \times \frac{P}{{D_\mathrm{e}}^2} \quad (1)$$

where D_e is the equivalent core diameter; $D_e^2=4A/\pi$ and $A=HD$ (H is the height of sample, mm); F is the size correction factor and $F=(\frac{D_e}{50})^{0.45}$.

Both L-type and N-type Schmidt hammer tests were conducted on block brick samples. Samples with a flat surface were prepared and smaller samples were clamped to a rigid base to prevent vibration during testing. At least 20 readings were recorded in each test and at least 10 higher rebound values were averaged (ISRM 2015). Table 3 shows the calculated results.

4 Results interpretation and comparison

4.1 Assumption validation

The strength of a brick may vary with clay content, firing temperature, pore distribution, and production method (Karaman, 2006; Azeez et al., 2011). Therefore, it is necessary to verify the validity of the assumption made in this study (brick samples used in this study were assumed to be homogeneous).

In the verification study, coefficient of variation (COV) (the ratio of standard deviation to mean value) of each test data (based on bricks) was calculated and the magnitude of COV was used to evaluate data discreteness (Kahraman, 2001). The calculated COV are listed in Table 3. It is known that COV of a homogeneous material does not exceed 10% (Allaby 2008). As shown in Table 3, only the COV of the brick sample D (COV of $I_{s(50)}$=17.9%) was larger than that limit (10%). Thus, the obtained data based on the brick sample D was discarded in the following analysis. In addition, the stress-strain curves of the bricks used in this study are compared with those of tested rocks (Fig 2). As shown in Fig 2, the stress-strain curves of the bricks used were quite similar in trend with that of the tested homogeneous Magnesian limestone and Woodkirk sandstone. Four-stage deformation characteristics, i.e., nonlinear, linear elastic, ductile region and post failure, were identified. Additionally, Young's moduli and Poisson's ratios of the tested brick samples were similar to that of ostensibly homogeneous rocks (Table 4). The above analysis and comparisons can be considered as a validation for the assumption made in the study.

4.2 Regression analysis

The regression analysis was conducted to find the best fitting curve of the UCS and the results of the index tests (on the homogeneous bricks). In statistical analysis, a *P*-value of no more than 0.05 and a confidence interval of 95% are often used to find the best fitting curve of two measured phenomena (Minitab manual 2014). The smallest standard error of regression (*S*), representing the average distance of data points departing from the regression line, is normally used to select the best equation (Forst 2014). The above principles were also used in this regression study. Fig. 3 shows the results of the regression analysis. The derived equations of UCS-$I_{s(50)}$, UCS-R_L and UCS-R_N are:

$$\mathrm{UCS} = 18.071 I_{s(50)} - 5.5 \quad (2)$$

$$\mathrm{UCS} = 1.80 \times 10^{-5} R_{\mathrm{L}}^{3.83} \quad (3)$$

$$\mathrm{UCS} = 0.30 R_{\mathrm{N}}^{1.43} \quad (4)$$

Corresponding parameters of the regression analysis are listed in Table 5. It can be seen that the magnitudes of the *P*-value of all index tests conducted in this study were 0 (smaller than the limit – 0.05, see Table 5), which demonstrates that there were a strong correlation between the UCS and the results of the index tests based on the homogeneous bricks. Furthermore, the point load tests exhibited a much higher reliability than the Schmidt hammer tests in the UCS estimation because the standard error (*S*) of results of the point load tests was the lowest (0.75, Table 5).

4.3 Comparison study

Fig 4 shows a comparison of the estimated UCS of the brick and rock samples using the derived equations in this study (Eqs. 2, 3 and 4) and their actual UCS values obtained in the uniaxial compression tests (Section 3). The estimated UCS are plotted against the actual UCS (only mean values are plotted for clarity). As shown in Figs 4a-4c, the calculated UCS values of the brick and rock samples based on the proposed equations clustered around the diagonal lines (red lines), especially for the homogeneous bricks, which indicates that the calculated UCS values are in broad agreement with those measured in the uniaxial compression tests. Interestingly, the derived UCS-$I_{s(50)}$ equation (Eq. 2) gave a somewhat smaller estimation of the UCS of all rock samples used in the study (see Fig 4a); and a slightly larger discrepancy was observed between the estimated UCS and measured UCS of the Woodkirk sandstone and Blackhill grit stone in comparison with that of the Magnesian limestone. The better UCS estimation of the Magnesian limestone using the Eq. (2) is probably due to its relatively finer grain size compared with that of the Woodkird sandstone (medium-grained) and the Blackhill grit stone (coarse-grained) (see Table 4). In addition, both UCS-R_L and UCS-R_N equations exhibited inferior capabilities of the UCS estimation for rocks, especially for the coarse-grained Blackhill grit stone (see Fig. 4c). It also can be seen that the negative effect of grain size on the point load test is more obvious than on the Schmidt hammer test (Figs 4a-4c).

Apart from the above quantitative comparison analysis, a qualitative study was also conducted by comparing the derived equations (Eqs. 2, 3 and 4) in this study and corresponding equations from literature (based on different lithology), as presented in Fig 5. The inclination of the UCS-$I_{s(50)}$ equation derived in this study (red dashed line in Fig 5a) was between the inclinations of results from previous studies (based on real rock). Furthermore, the UCS-$I_{s(50)}$ equation obtained in this study was quite similar to those equations proposed by Singh (1981), Ulusay et al. (1994) and Karaman et al. (2015), whose tests were conducted using sandy shale, medium-grained sandstone and limestone, respectively. The UCS-R_L and UCS-R_N relationships obtained in this study were also similar to those proposed by Yaşar and Erdoğan (2004) and Kılıç and Teymen (2008), respectively (Figs 5b and 5c).

5 Conclusion

In this study, the validity of index tests in the estimation of UCS of rock was studied using a series of uniform and homogeneous brick samples. Three equations of UCS-$I_{s(50)}$, UCS-R_L and UCS-R_N were proposed based on the results of point load tests and the Schmidt hammer tests on homogeneous material. One conclusion from this study is that there was a strong correlation between UCS and index test results when homogeneous bricks were used, which indicates that UCS of rock can be estimated accurately when lithological heterogeneity was removed. It is suggested that, in the UCS estimation using index tests, homogeneous rock samples should be used to get a reliable result. Based on the test results and analysis in the study, the point load tests exhibited a somewhat higher accuracy in the UCS estimation, which is therefore suggested for estimating the UCS of rock.

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Fig Captions

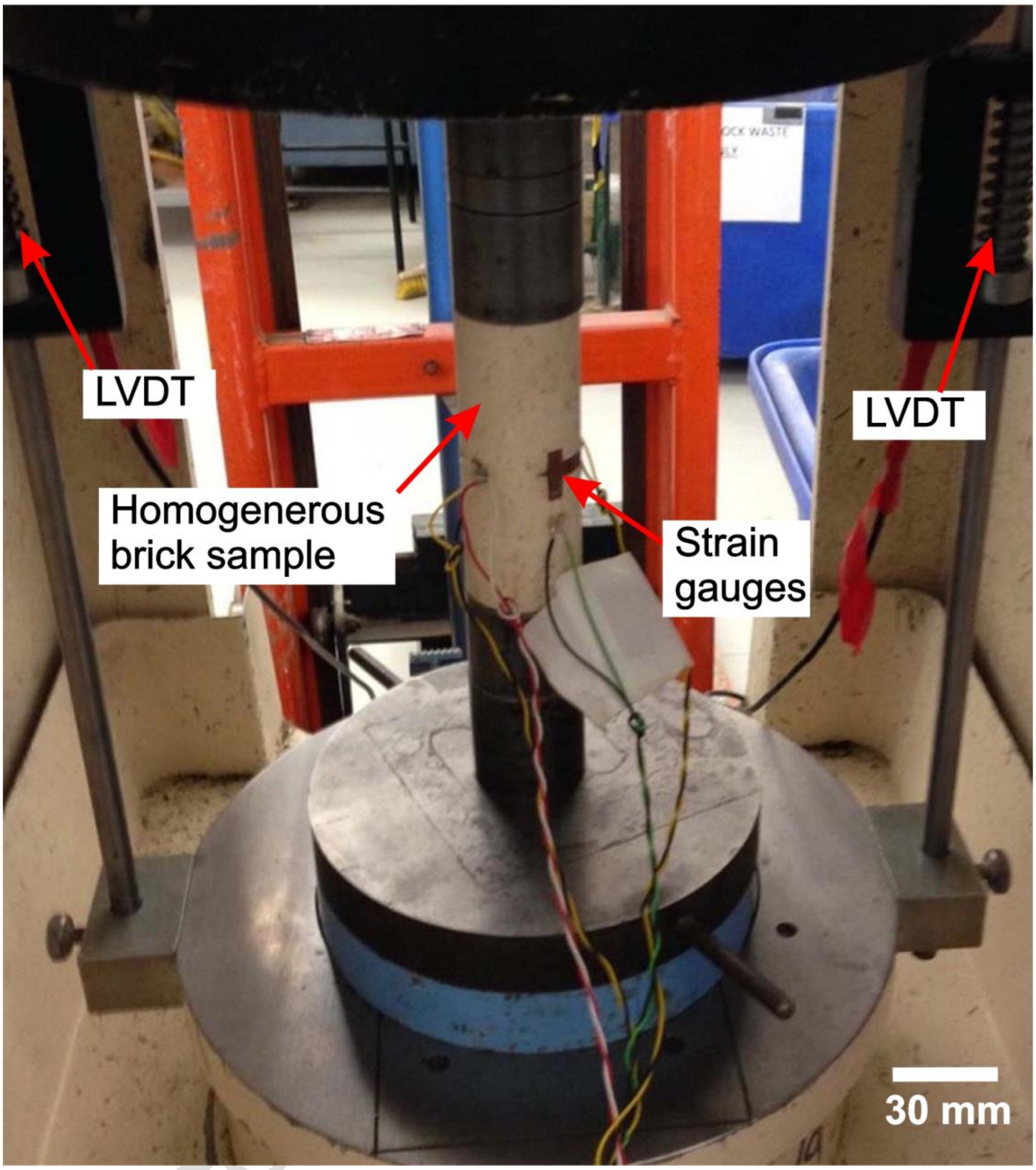
Fig 1 Experimental setup of the uniaxial compression test on a brick sample.

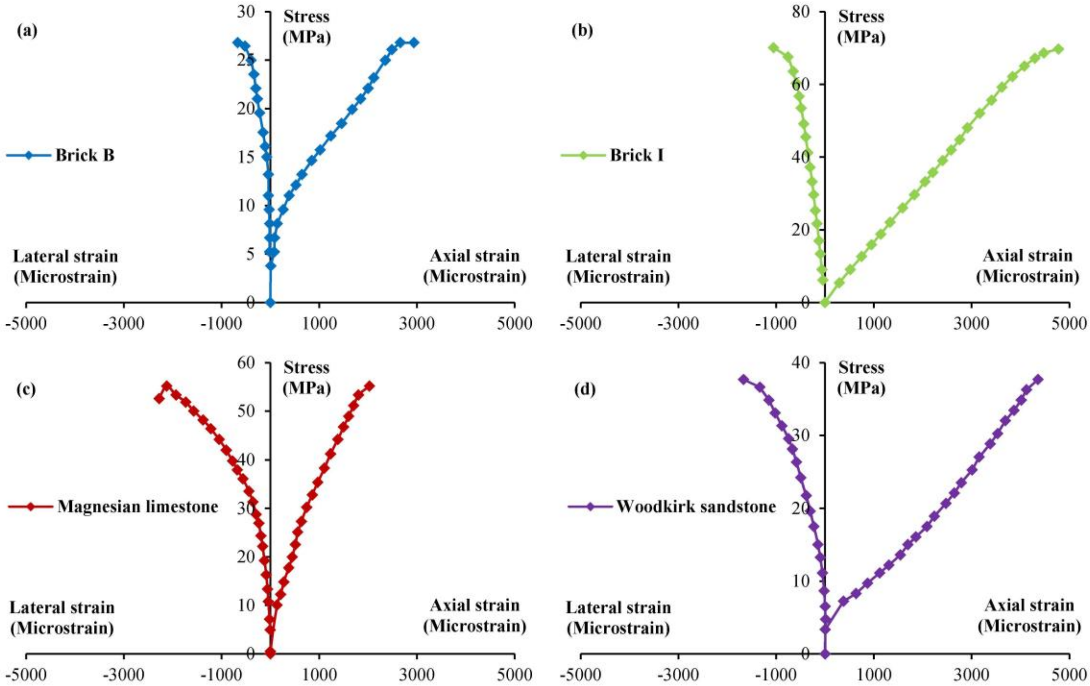
Fig 2 Representative stress-strain curves of tested rock and brick samples.

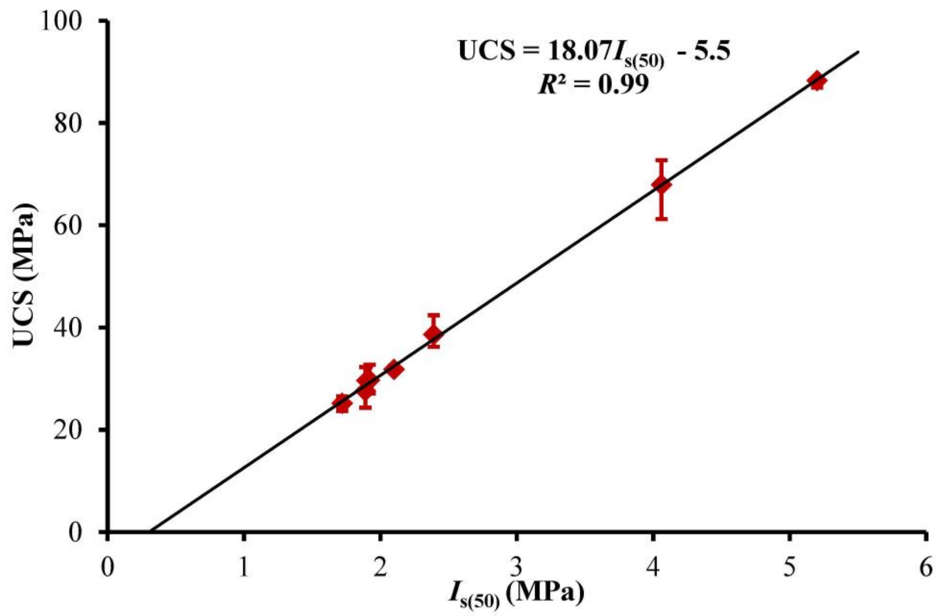
Fig 3 Relationship between UCS and results of the index tests of the homogeneous brick samples tested. (**a**) UCS against $I_{s(50)}$. UCS versus the rebound values of the L-type Schmidt hammer (**b**) and the N-type Schmidt hammer (**c**).

Fig 4 Comparisons of the estimated UCS using the proposed equations (Eq. 2 (**a**), Eq. 3 (**b**) and Eq. 4(**c**)) and corresponding measured UCS using the unconfined compression tests.

Fig 5 Comparisons of the UCS-$I_{s(50)}$ (**a**) , UCS-R_L (**b**) and UCS-R_N (**c**) relationships from previous investigations and corresponding ones proposed in this study.


LVDT
LVDT
Homogenerous
brick sample
Strain
gauges
30 mm


(a)
Stress (MPa)
Brick B
Lateral strain (Microstrain)
Axial strain (Microstrain)
(b)
Stress (MPa)
Brick I
Lateral strain (Microstrain)
Axial strain (Microstrain)
(c)
Stress (MPa)
Magnesian limestone
Lateral strain (Microstrain)
Axial strain (Microstrain)
(d)
Stress (MPa)
Woodkirk sandstone
Lateral strain (Microstrain)
Axial strain (Microstrain)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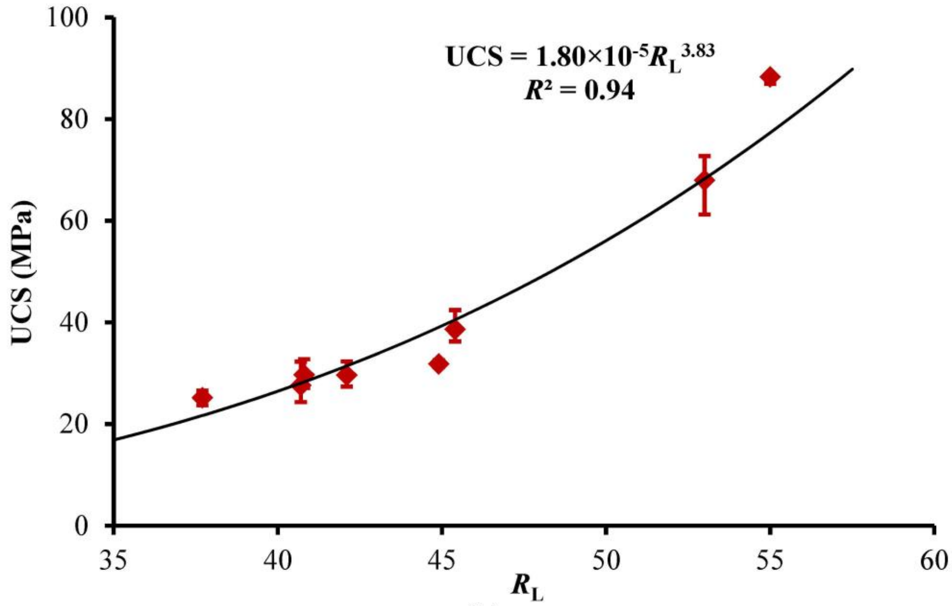
R^2 = 0.99
UCS (MPa)
$I_{s(50)}$ (MPa)

(a)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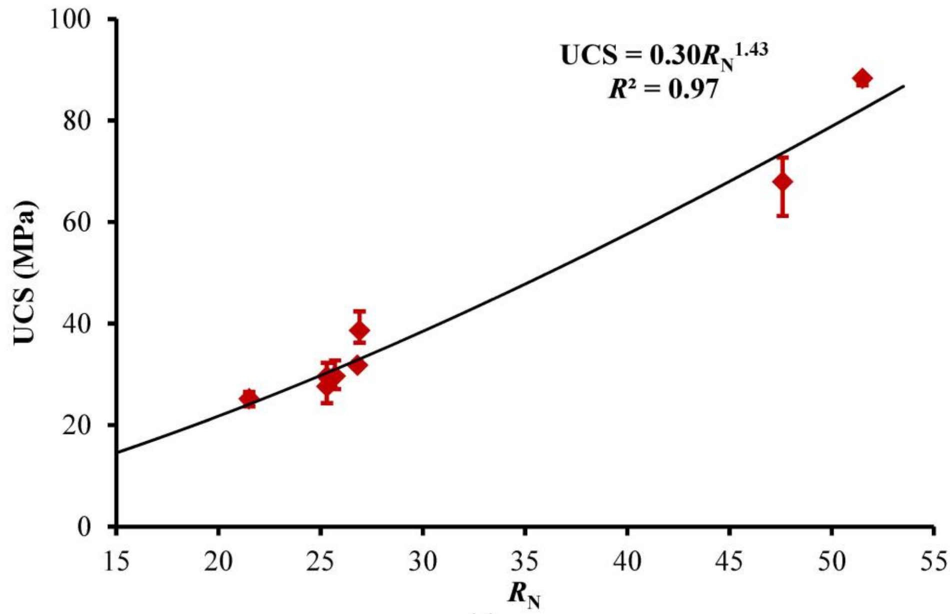
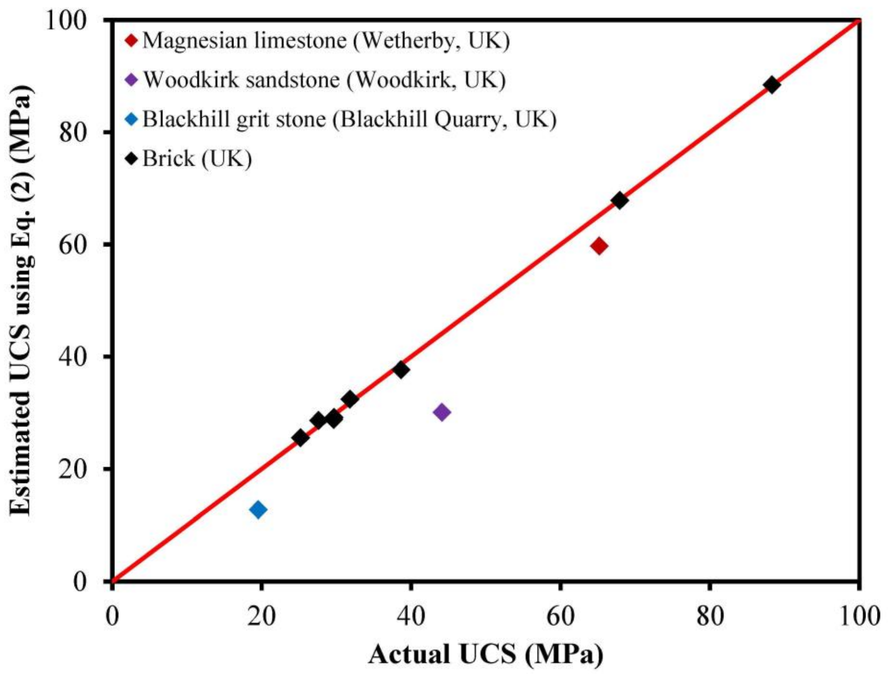
R^2 = 0.94
UCS (MPa)
R_L

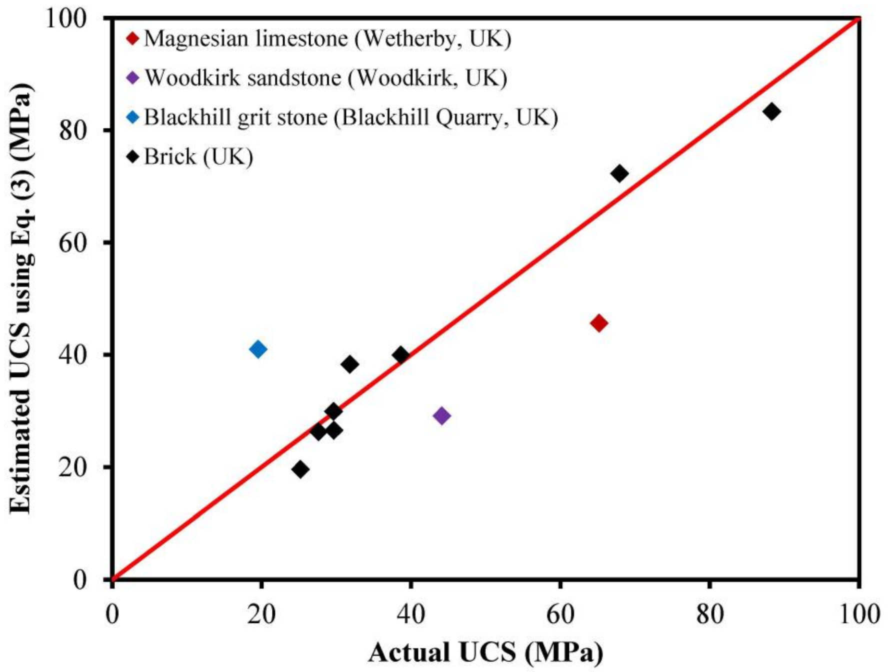
(b)


UCS = 0.30$R_N^{1.43}$
R^2 = 0.97
UCS (MPa)
R_N
100
80
60
40
20
0
15
20
25
30
35
40
45
50
55

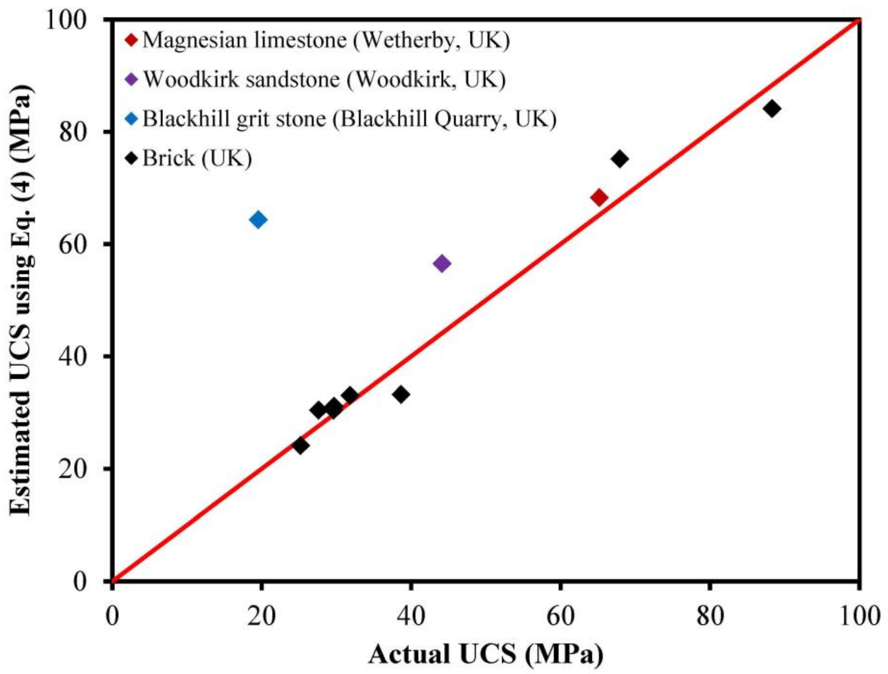
(c)


Magnesian limestone (Wetherby, UK)
Woodkirk sandstone (Woodkirk, UK)
Blackhill grit stone (Blackhill Quarry, UK)
Brick (UK)
Estimated UCS using Eq. (2) (MPa)
Actual UCS (MPa)
100
80
60
40
20
0

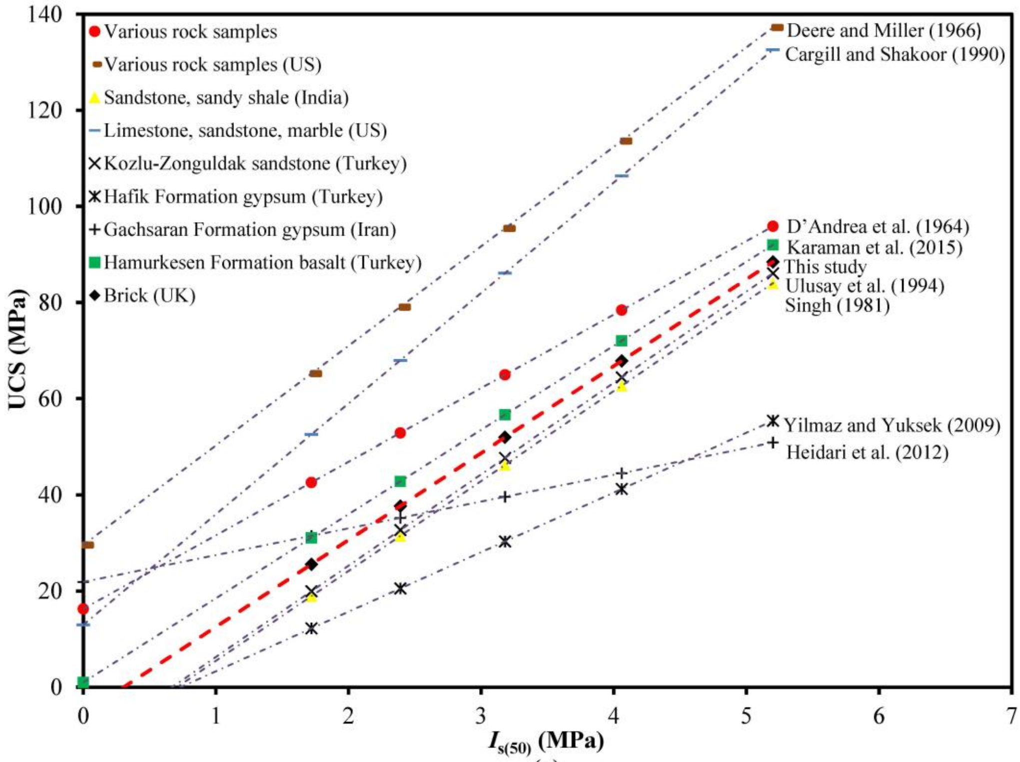
(a)


100
80
60
40
20
0
Estimated UCS using Eq. (3) (MPa)
Magnesian limestone (Wetherby, UK)
Woodkirk sandstone (Woodkirk, UK)
Blackhill grit stone (Blackhill Quarry, UK)
Brick (UK)
0
20
40
60
80
100
Actual UCS (MPa)

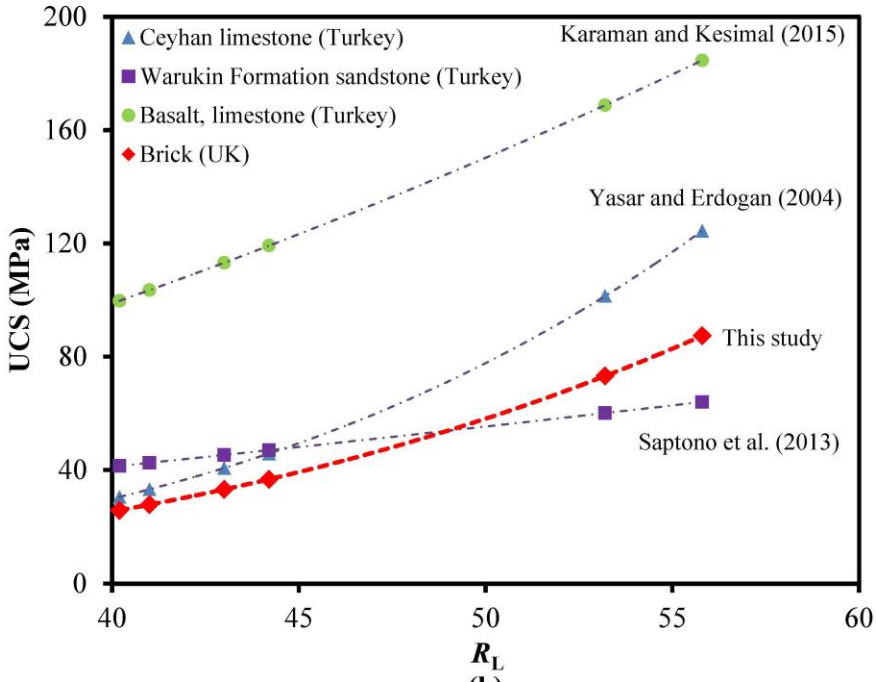
(b)


100
80
60
40
20
0
Estimated UCS using Eq. (4) (MPa)
Magnesian limestone (Wetherby, UK)
Woodkirk sandstone (Woodkirk, UK)
Blackhill grit stone (Blackhill Quarry, UK)
Brick (UK)
0
20
40
60
80
100
Actual UCS (MPa)

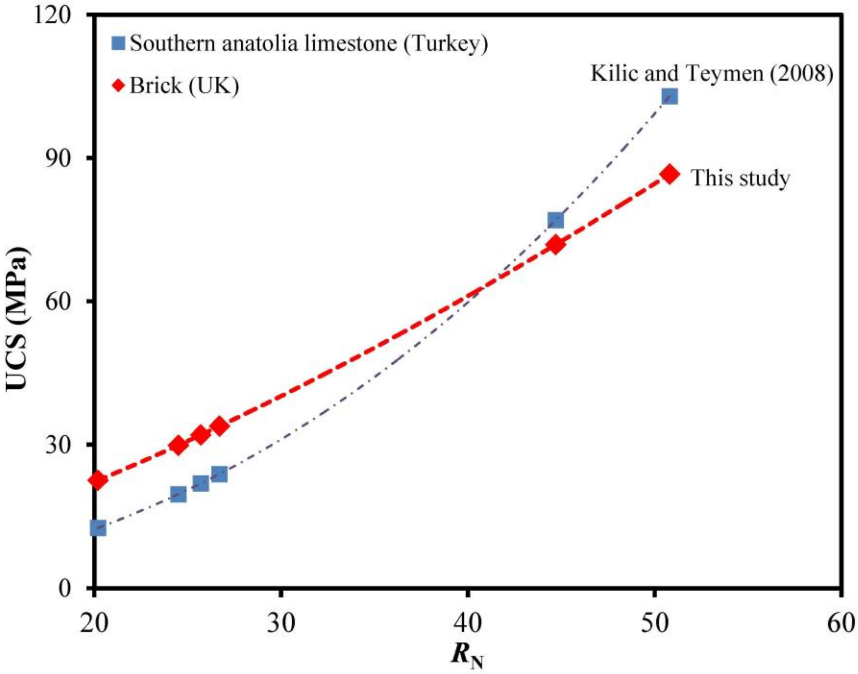
(c)


Various rock samples
Various rock samples (US)
Sandstone, sandy shale (India)
Limestone, sandstone, marble (US)
Kozlu-Zonguldak sandstone (Turkey)
Hafik Formation gypsum (Turkey)
Gachsaran Formation gypsum (Iran)
Hamurkesen Formation basalt (Turkey)
Brick (UK)
Deere and Miller (1966)
Cargill and Shakoor (1990)
D'Andrea et al. (1964)
Karaman et al. (2015)
This study
Ulusay et al. (1994)
Singh (1981)
Yilmaz and Yuksek (2009)
Heidari et al. (2012)
UCS (MPa)
$I_{s(50)}$ (MPa)
(a)

373


Ceyhan limestone (Turkey)
Warukin Formation sandstone (Turkey)
Basalt, limestone (Turkey)
Brick (UK)
Karaman and Kesimal (2015)
Yasar and Erdogan (2004)
This study
Saptono et al. (2013)
UCS (MPa)
R_L
(b)

374


120
90
60
30
0
UCS (MPa)
Southern anatolia limestone (Turkey)
Brick (UK)
Kilic and Teymen (2008)
This study
20
30
40
50
60
R_N

(c)